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Long-term underwater sound measurements in the shipping noise indicator bands 63 Hz and 125 Hz from the port of Falmouth Bay, UK

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ABSTRACT

Chronic low-frequency anthropogenic sound, such as shipping noise, may be negatively affecting marine life. The EU's Marine Strategy Framework Directive (MSFD) includes a specific indicator focused on this noise. This indicator is the yearly average sound level in third-octave bands with centre frequencies at 63 Hz and 125 Hz. These levels are described for Falmouth Bay, UK, an active port at the entrance to the English Channel. Underwater sound was recorded for 30 min h⁻¹ over the period June 2012 to November 2013 for a total of 435 days. Mean third-octave levels were louder in the 125-Hz band (annual mean level of 96.0 dB re 1 µPa) than in the 63-Hz band (92.6 dB re 1 µPa). These levels and variations are assessed as a function of seasons, shipping activity and wave height, providing comparison points for future monitoring activities, including the MSFD and emerging international regulation.

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1. Introduction

There is growing recognition that underwater anthropogenic sound may negatively impact marine species. Loud impulsive sounds, such as from seismic air guns or pile driving, have been considered to pose the greatest risk to marine species (Southall et al., 2007) but yet can also contribute to chronic noise at far distances (Gordon et al., 2003). Rising average sound levels (Andrew et al., 2002; McDonald et al., 2006), mainly from increases in commercial shipping (McDonald et al., 2008), have led to concern that the chronic presence of non-impulsive low-frequency anthropogenic noise may also affect marine species (Popper and Hastings, 2009; Slabbekoorn et al., 2010). Potential effects include increasing stress (Rolland et al., 2012; Wysocki et al., 2006), masking signals (Clark et al., 2009; Lucke et al., 2007), or causing behavioural responses (Castellote et al., 2012; Dyndo et al., 2015) with possible consequences for breeding success (Croll et al., 2002), predator avoidance (Picciulin et al., 2012; Simpson et al., 2015), and habitat avoidance (Bryant et al., 1984; Miksis-Olds et al., 2007).

The EU's Marine Strategy Framework Directive (MSFD) requires member states to attain Good Environmental Status (GES) in their seas by 2020, through the development of indicators, associated

management strategies, and monitoring programmes (The European Parliament and the Council of the European Union, 2008). To address and mitigate potential concerns about underwater noise pollution, the MSFD manages anthropogenic noise with a component termed Descriptor 11. The descriptor states that energy emissions, including underwater noise, must not adversely affect the marine environment (The European Parliament and the Council of the European Union, 2008). The determination of GES is particularly challenging for underwater noise as there is often limited evidence on current sound levels, trends, and likely effects on marine species (Slabbekoorn et al., 2010; Van der Graaf et al., 2012), although the volume of published literature is now steadily increasing (Williams et al., 2015). There is, in particular, a pressing need for further research to understand ambient noise levels in European coastal seas (Dekeling et al., 2013; Van der Graaf et al., 2012). Shallow water (<200 m) ambient levels are expected to be louder (Wenz, 1962) and more variable than in deep water (Merchant et al., 2012b; Richardson et al., 1995; Urlick, 1983). This may make selecting representative sites for monitoring all the more challenging.

The regulation of underwater noise has, thus far, largely been achieved under Environmental Impact Assessment requirements (Dolman et al., 2009; European Union, 2013); marine mammal protection, such as the Marine Mammal Protection Act in the USA (Horowitz and Jasny, 2007), the Joint Nature Conservation Committee's (JNCC; UK) guidelines for mitigation of the effects of seismic surveys (Joint Nature Conservation Committee, 2010), and marine protected areas legislation (Haren, 2007). European MSFD regulations are the first

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international regulations with specific targets for underwater noise emissions. The International Maritime Organization (IMO) has recognised the negative impact of shipping on underwater noise levels and has recently introduced voluntary guidelines aimed at ship designers, builders, and operators with the aim of reducing the contribution of commercial shipping to underwater noise levels (International Maritime Organization, 2013). Additionally, a meeting of stakeholders and experts in the shipping industry proposed international targets to reduce the contribution of shipping to ambient noise levels in the frequency range 10 Hz to 300 Hz by 3 dB in 10 years and by 10 dB in 30 years relative to current levels (Wright, 2008). With the potential for definitions of other international targets on shipping noise, information regarding the use of the MSFD indicators is all the more important.

The latest guidance describes two attributes for Descriptor 11: low- and mid-frequency impulsive sound (10 Hz to 10 kHz); and low-frequency continuous sound where the focus is shipping noise (Dekeling et al., 2013; Tasker et al., 2010). The average yearly sound levels in third-octave bands with centre frequencies at 63 Hz and 125 Hz have been set as the indicator for the second attribute. Third-octave bands are described by the sum of the sound power occurring within defined frequency bands, one third of an octave wide. Propeller cavitation noise, from vessels underway, is known to peak in the frequency range 50–150 Hz (Ross, 1976). These two third-octave bands are therefore considered to capture the anthropogenic contribution from shipping while also minimising the input from natural sources (Tasker et al., 2010). Additionally, third-octave bands are often used in studies of masking in marine mammals (Jensen et al., 2009; Madsen et al., 2006; Richardson et al., 1995) as approximately, in mammalian hearing, a sound is considered to affect the audibility of any other sounds with a frequency within the same third-octave band (Fay, 1988; NRC, 2003). The latest interpretation of the indicator is that trends in annual averages should be monitored to facilitate the assessment of GES (Van der Graaf et al., 2012). As determining statistically significant trends in underwater noise may take years to decades, monitoring of absolute levels is also recommended (Dekeling et al., 2013).

Measurements of low-frequency third-octave levels have taken place at many locations around the world and range from short- (minutes) to long-term (up to 7 years). This includes the following: on the continental slope offshore California, within 10–500 Hz for 7 years (Andrew et al., 2002); in deep waters such as in the SOFAR channel in the Atlantic, Indian, and Pacific Oceans using hydroacoustic explosion-monitoring stations at <125 Hz for 42 months (van der Schaar et al., 2014); and offshore British Columbia at <1.6 kHz for 4 months (Merchant et al., 2012a) and at a shallow archipelago in Croatia with touristic boating activity between 63 Hz and 20 kHz for 5 min month⁻¹ over 2 years (Rako et al., 2013). Measurements have also occurred in association with monitoring of industrial activities, including shallow dredging operations in New York Harbour within 20 Hz–20 kHz (Reine et al., 2014), dock activities in Hong Kong from 10 Hz to 16 kHz over 4 days (Wursig and Greene, 2002), and operation of wind turbines in Denmark and Sweden at <500 Hz for up to 10 min at a time (Tougaard et al., 2009).

These empirical studies are complemented by modelling, e.g., for shipping on the west coast of Canada, where areas with calculated yearly averages over 100 dB re 1 μ Pa in the 63-Hz and 125-Hz third-octave bands were identified (Erbe et al., 2012).

European coastal waters have benefited from few long-term measurements shared in peer-reviewed literature. Within the context of a need for more long-term information on the levels and trends of the MSFD indicator third-octave bands (63 Hz and 125 Hz), we set out to describe measurements taken over 14 months (435 days) in Falmouth Bay, UK, a busy port environment at the entrance to the English Channel, one of the world's busiest shipping environments. These coastal locations likely represent one of the greatest challenges to the management of anthropogenic noise due to the high level of

anthropogenic use, the presence of complex sound fields, and the variety of sources, including from a range of vessel types.

2. Materials and methods

2.1. Location

Falmouth Harbour and its outer Bay (Fig. 1) support a commercial port with 1193 and 783 ship arrivals in 2012 and 2013, respectively (Department for Transport Statistics, 2013, 2014). The port is the second most active port in the South West of the UK (Department for Transport Statistics, 2013), and most visiting vessels are tankers or dry cargo ships. Falmouth Bay is located adjacent to the international shipping lanes through the English Channel, bordered by the south coast of the UK and north-west coast of France. In addition to vessels transiting the bay when arriving and departing, vessels also anchor within the bay, e.g., for bunkering (Merchant et al., 2012b). The region also supports considerable recreational boating (Latham et al., 2012), small-scale and industrial fisheries, and a developing renewable energy sector. Host ecosystems in Falmouth Bay support a diverse range of mobile marine fauna, including dolphins, harbour porpoises (Pikesley et al., 2012), basking sharks (Witt et al., 2012), and grey seals (Leeney et al., 2010). The port area hosts a UK Special Area of Conservation, which contains sandbanks with eelgrass and Maerl beds (SAC; Joint Nature Conservation Committee (2011)), a Marine Conservation Zone (MCZ) containing sea-fans (Defra, 2013), and there is a proposed Special Protected Area (pSPA) for overwintering seabird species (Natural England, 2014).

2.2. Noise monitoring

Two autonomous multichannel acoustic recorders (AMAR G2; Jasco Applied Sciences; 24-bit recording using manufacturer-calibrated GeoSpectrum M8E hydrophones) were alternately deployed at FaBTest, a wave energy test site in Falmouth Bay. AMARs were programmed to record for the first 30 min in every hour for the period June 2012 to November 2013 at a sampling frequency of 64 kHz, with a resulting usable frequency range of 10 Hz to 32 kHz. The hydrophone has a nominal sensitivity of -165 dB re 1 V/ μ Pa, predominantly flat within 100 Hz–10 kHz (Jasco Applied Sciences). A pistonphone was used (type 42AC; G.R.A.S., Denmark) to test the system's response at 250 Hz, which was a maximum of 1.3 dB different to the expected value by the end of the study. Selected deployments were also accompanied by a device recording conductivity (mS cm⁻¹), temperature (°C), and pressure (depth; m), sampling at 20-s intervals (XR-420; RBR Ltd). AMARs were deployed using a syntactic foam flotation collar (Jasco Applied Sciences Ltd), with the device floating in the water column ~10–15 m from the seabed at depths ranging from approximately 30 to 45 m. The hydrophone on each AMAR was protected by an external cage and covered in a cloth shroud (hat). This shroud was used in all but the first deployment (Table 1). To account for this, the data from each deployment were processed separately, and the effect of the shroud was assessed during the statistical analysis. For the purpose of this study, acoustic data gathered during the operational periods of the nearby (~200 m) wave energy converter at the FaBTest site were eliminated (Table 1).

2.3. Acoustic data processing

Following each AMAR deployment, data were downloaded and converted to .wav file format using proprietary software (Jasco Applied Sciences Ltd). Matlab (The Mathworks; Massachusetts) scripts were developed to process the acoustic data. Hydrophone response curves provided by the manufacturer's calibration process were interpolated linearly to provide a hydrophone sensitivity value per 1 Hz and used to calibrate the data with an acoustic gain of 0 dB. A Fast Fourier Transform (FFT) function was applied to each 30-min acoustic recording to

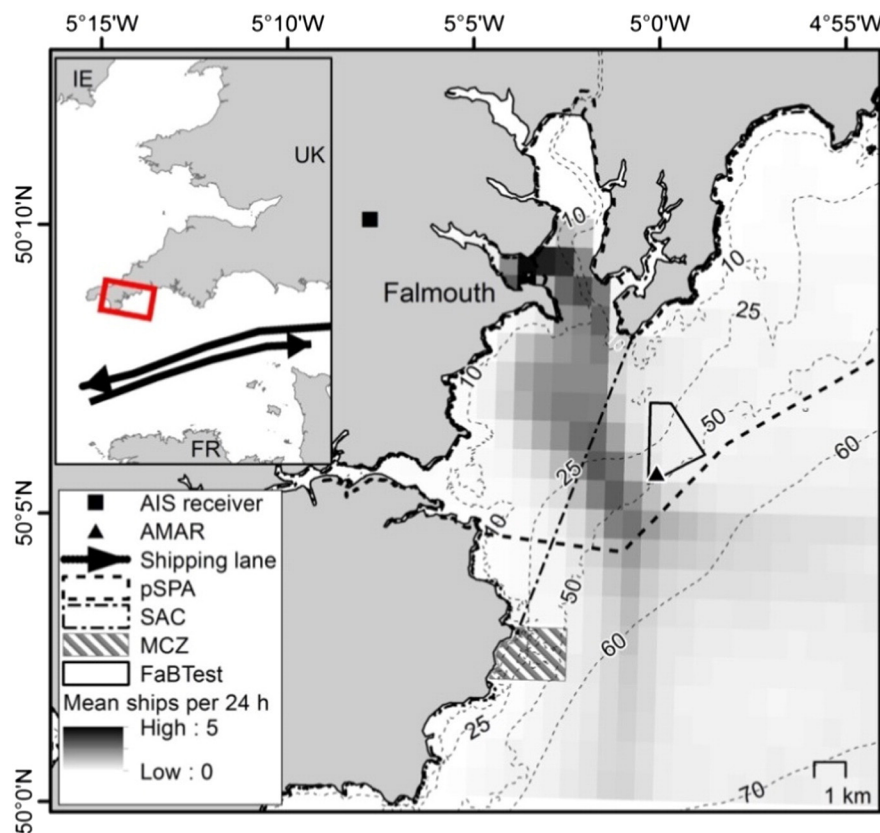


Fig. 1. Map of Falmouth Bay with 10-m depth contours to 70-m depth. The geographical limits of the vessel Automatic Identification System (AIS) data collection are given by the eastern and southern limits of the map. FaBTest is the Falmouth Bay Test site for marine renewables, in which the Autonomous Multichannel Acoustic Recorder (AMAR) was deployed. Areas of importance for marine wildlife are also highlighted: pSPA, proposed Special Protected Area; SAC, Special Area of Conservation; MCZ, Marine Conservation Zone.

provide a power spectral density (PSD) in square pressure (p_{RMS}^2). The FFT used a 1-s Hann window, with a 50% overlap and a scaling factor of 0.5 to remove the effect of the Hann window on the resulting amplitude (Cerna and Harvey, 2000). A noise power bandwidth correction of 1.5 was also applied to give a 1-Hz frequency resolution (Cerna and Harvey, 2000; Merchant et al., 2013). The means of the square pressure values were calculated per minute per Hz to facilitate practical data storage requirements and computation time while maintaining a fine time resolution. To calculate third-octave levels for each 30-min acoustic recording, the mean minute square pressure values were summed together, within the frequency range 57–71 Hz (63 Hz third-octave band) and 113–141 Hz (125 Hz third-octave band) to provide a third-octave level for each 1-min period. Their means were calculated for each file to provide a 30-min mean third-octave level. To facilitate comparison of our data with other studies, and for the identification of

trends, 24-h running-mean third-octave levels were calculated by taking the centred-mean of 24 consecutive 30-min mean third-octave levels. Seasonal patterns in third-octave levels were investigated by grouping the 30-min mean third-octave levels according to season (Spring; March–May, Summer; June–August, Autumn; September–November, Winter; December–February). The resulting values were then converted to dB, with the standard reference pressure of 1 μPa , once all processing and averaging was completed. The mean square pressure (p_{RMS}^2), or arithmetic mean, as well as percentile levels from p_{RMS}^2 have been used in line with the latest recommendations (Van der Graaf et al., 2012).

2.4. Tide and wave data

Tidal data (flow rate; metres s^{-1}) for the location of the AMAR deployment were obtained from the POLPRED depth-averaged high-

Table 1
Deployment history of AMARs in Falmouth Bay.

Deployment number	Date of deployment	Position (degrees; WGS84)	Number of days of recording	Number of 30-min files	Number of 30-min files used in further analysis	% of 30-min files used
1	13th June–20th August 2012	N50.098889 W04.995278	68.0	1634	1522	93.1
*2	20th August–8th November 2012	N50.100409 W04.996118	81.4	1954	1497	76.6
*3	8th November 2012–9th January 2013	N50.100633 W04.995900	62.1	1489	1038	69.7
*4	09th January–11th March 2013	N50.101256 W04.996308	61.4	1474	922	62.6
*6	04th June–8th August 2013	N50.100283 W04.997333	77.0	1848	1271	68.8
*7	8th August–4th November 2013	N50.100167 W04.998050	98.2	2311	1946	84.2

* During deployments 2 to 7, the hydrophone cage was covered with a cloth shroud to reduce flow noise.

resolution UKCS Model CS20-15HC (horizontal resolution approximately 1.8 km; National Oceanography Centre (UK)). Wave height data were obtained from a Seawatch Mini II directional wave buoy (Fugro 2010) deployed at the FaBTest site, approximately 150 m from the AMAR location. The wave buoy sampled at a frequency of 2 Hz for 1024 s every 30 min. These data were processed using proprietary software (WaveSense, Fugro OCEANOR AS, Norway) to provide a mean significant wave height for each 30-min period (Ashton et al., 2013).

2.5. Vessel traffic

To quantify the presence of AIS-transmitting vessels in the bay, and their likely contribution to recorded sound levels, data from the Automatic Identification System (AIS) were used (International Maritime Organization, 2001). All ships larger than 300 gross tonnes on international passages, cargo ships larger than 500 gross tonnes on any passage, and all passenger vessels are required to carry AIS. Other vessels may carry AIS voluntarily. The system transmits information via VHF, including ship identity, position, and course. AIS should be operational when ships are underway or at anchor (International Maritime Organization, 2001). Estimates of the number of vessels occupying Falmouth Bay during each day were calculated from available AIS data for the period of 1st June 2013 to 31st July 2014; and for each 30-min acoustic recording for the period of 1st June 2013 to 14th November 2013. AIS data occurring outside the Falmouth Bay area were excluded (Northerly extent: 50.223°N, southerly extent: 50.005°N, westerly extent: -5.128°E , easterly extent: -4.869°E). AIS data were obtained from an AIS-receiving antenna located at 50.170784°N $-5.127575^{\circ}\text{E}$.

2.6. Statistical modelling

To investigate the influence of the natural environmental contributions of tide speed and wave height to the shipping noise indicator bands, we used a Generalised Linear Model in R (R Development Core Team, 2008). Of the available error structures, a Gamma distribution exhibited the best fit with the third-octave level data and was specified within the model. The 30-min mean third-octave level data for the 63- and 125-Hz third-octave bands were modelled separately and acted as response variates in their respective models. The sound data from each deployment were combined to provide a single time series of third-octave levels with the corresponding wave height (H_s ; m) and modelled tide speed (m s^{-1}). The wave height data were not a complete data set, and the associated data from periods of time without wave height data were removed for the purpose of statistical modelling. The period with the lowest data coverage was July and August 2013 where there was data for 43% of this period. In total, there were 284 days of data, i.e., 55% data coverage. For each band, the full model included wave height, tide speed, presence of cloth shroud, and the interaction between cloth shroud and tide speed. Explanatory variables or their interactions found to be insignificant (with a p value >0.05) were removed during model simplification. The full model and simplified models were tested for significant differences (ANOVA).

To investigate the additional influence of shipping intensity (the number of AIS-enabled vessels in Falmouth Bay) on our estimates of sound recorded in the 63- and 125-Hz third-octave bands, we used the same modelling process and data sources as above for the shorter time period 5th June to 14th November 2013 where both underwater sound and contemporaneous AIS data were available. The number of vessels per 30 min was included as an explanatory variable. The 30-min mean third-octave level data for the 63- and 125-Hz third-octave bands were modelled separately and acted as response variates in their respective models. Results from modelling were validated with diagnostic plots including examining residuals versus their fitted values.

2.7. Sampling effort analysis

For each deployment, mean third-octave levels were derived for sub-samples of sequentially increasing data sets of 30-min mean levels (for both the 63- and 125-Hz data sets) to determine relationships between sampling duration (effort) and estimates of mean levels (Supplemental Table 4). The samples consisted of consecutive recordings for 24 h and 48 h, 5 days (120 h), 10 days (240 h), 20 days (480 h), 30 days (720 h), 40 days (960 h), and 50 days (1200 h) where there was at least 95% data coverage for the required duration (Suppl. Table 4).

3. Results

Underwater sound data were collected from 13th June 2012 to 14th November 2013 providing 435 days of data (84% data coverage). Acoustic data were not available from March to May 2013, as data were lost during recovery. Other gaps in data availability were due to weather conditions preventing access to the site for instrument recovery or servicing, or operational activity from the wave energy converter, for a total of 98 days. The AMAR operated for a mean of 75 days per deployment (Table 1).

3.1. The 63-Hz and the 125-Hz mean third-octave levels

Both third-octave indicator bands demonstrated high levels of variation, with the greatest variation exhibited by the 63-Hz band (range of 30-min mean levels from 43.3 dB to 59.5 dB and from 34.9 to 46.6 dB per deployment for the 63-Hz and 125-Hz third-octave bands, respectively; Fig. 2 and Suppl. Fig. 1; Suppl. Tables 1 and 2). Third-octave levels were louder within the 125-Hz band (by a mean of 4.3 dB by deployment) as compared to the 63-Hz band, more often exceeding 100 dB (Suppl. Table 1). An increasing trend in third-octave levels was identified for the 125-Hz band between August 2012 and February 2013, with quieter average sound levels later in 2013 (Fig. 2 and Suppl. Fig. 1, Suppl. Table 3). A similar pattern was identified in the 63-Hz third-octave levels, although the loudest levels were different for each band, with the 3rd and 4th deployments exhibiting the loudest overall mean level for the 63-Hz and 125-Hz third-octave bands, respectively (Suppl. Table 1).

3.2. Seasonal third-octave levels

Sound levels varied by season, with winter 2012/13 exhibiting the loudest mean third-octave levels in both the 63-Hz and the 125-Hz bands (Fig. 3, Suppl. Table 3). The seasonal patterns differed between bands, as although the summer period was quietest for the 63-Hz band in both years, in the 125-Hz band, the mean summer 2013 level was louder than the autumn 2013 level (Fig. 3, Suppl. Table 3). Conversely, the median of the 30-min mean third-octave levels was quieter (lower) in summer 2013 than autumn 2013 for the 125-Hz band (Fig. 3) most likely indicating loud transient sounds in summer 2013, which can strongly affect the arithmetic means (Merchant et al., 2012a).

The median wave height (H_s ; m) also varied by season. It was 0.6 m in both Spring and Autumn and it was 0.5 m and 1.0 m in Summer and Winter, respectively.

3.3. Annual third-octave levels

Mean sound levels were quieter in 2013 than in 2012, for the comparative period 14th June to 14th November (154 days), a period when AMARs were fully operational in both years, with differences of -2.0 dB and -1.4 dB for the 63-Hz and 125-Hz bands, respectively (Table 2).

The MSFD indicator requires measurement of a yearly mean third-octave level for each of the 63-Hz and 12-Hz indicator bands. Long-term levels are calculated over multiple deployments according to the

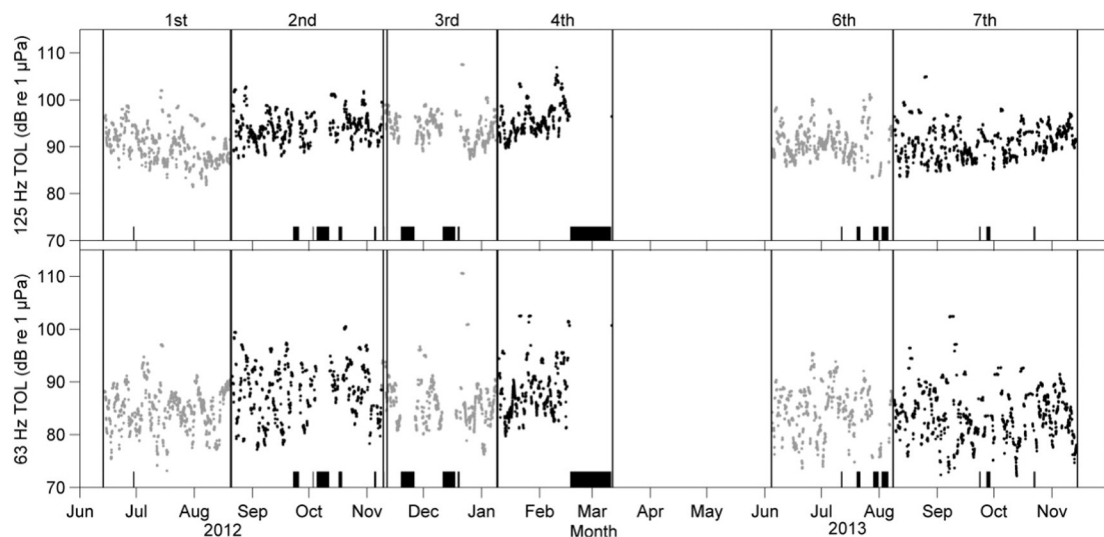


Fig. 2. Twenty-four hour centred mean third-octave levels for the 63-Hz and 125-Hz bands from square pressure (p_{RMS}^2); 1st–7th indicates deployment number. Data from deployment 5 were lost during recovery. Other gaps in the data were due to the exclusion of data due to operational activity of the WEC. Vertical markers indicate where WEC operational activity occurred for 24 h or more. Note the y axis is displayed from 70 dB re 1 μ Pa.

period covered and deployment configurations (Table 3). This includes mean and percentile values covering 12 months from deployments 2 to 6, which had identical configurations, although this also contains a break in the data from March to May 2013 (Table 3).

3.4. Natural environmental contributions

Tide speed, wave height (scaled deviance (D^*) = 588.59, $p < 0.001$), and the interaction of the shroud and tide speed (D^* = 165.43, $p < 0.001$) were all found to significantly affect the 63-Hz band noise levels.

For the 125-Hz band, during model simplification, both tide speed ($p = 0.0651$) and the interaction between tide speed and shroud ($p = 0.1210$) were found not to be significant and were removed

from the model. Wave height (D^* = 181.45, $p < 0.001$) and the presence of the shroud (D^* = 364.66, $p < 0.001$) were both found to be significant.

The median sound levels during 1 min of peak tide speed at every high and low tide during the 2nd deployment, without a shroud, was 77.7 dB re 1 μ Pa, while at other times, it was 4.8 dB quieter at 72.9 dB. During the 3rd deployment, with the presence of a shroud, the median sound level at peak tide speeds was 76.4 dB re 1 μ Pa compared to a quieter median sound level by 1.3 dB of 75.1 dB at other times. The difference in sound level was reduced by 3.5 dB with the presence of a shroud.

3.5. Vessel traffic

Highest shipping densities occurred in Falmouth Harbour at the entrance to Falmouth Bay, with moderate densities in the outer bay (Fig. 1). The number of vessels visiting Falmouth Bay per day varied by season, with fewest in winter 2013/14 and the most in summer (2012 and 2013; Fig. 4).

For the model including number of AIS-transmitting vessels, there was a significant effect of tidal speed (D^* = 33.442, $p < 0.001$), wave height (D^* = 134.663, $p < 0.05$), and number of AIS transmitting vessels (D^* = 53.257, $p < 0.001$) for the 63-Hz band. For the 125-Hz band, there was a significant effect of wave height (D^* = 27.425, $p < 0.001$) and number of AIS-transmitting vessels (D^* = 13.847, $p < 0.001$). Tidal speed was not found to be significant in the GLM for the 125-Hz band.

3.6. Sampling effort

The deployments are analysed separately to ensure consistency with the recording equipment although the deployments approximately correspond to seasons of the year. The 1st and 6th deployments approximately correspond to summer, the 2nd and 7th deployments consist predominantly of autumnal months, and the 3rd and 4th deployments

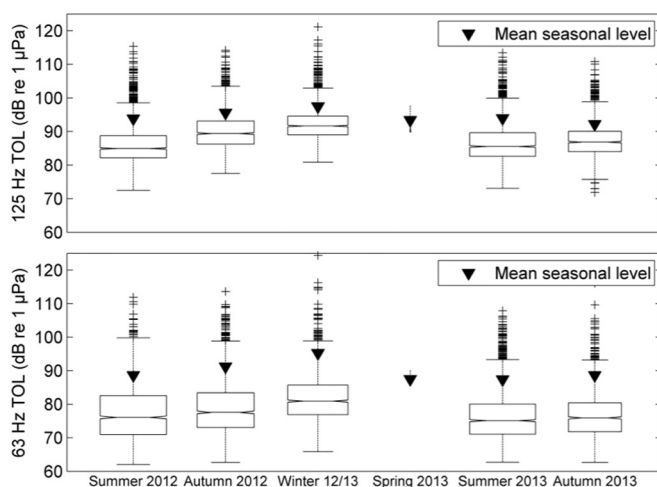


Fig. 3. Mean and median third-octave levels by season (Spring: March–May, Summer: June–August, Autumn: September–November, Winter: December–February). The median is given by the centre of the box. The 25th and 75th percentiles are given by the upper and lower bounds of the box, respectively. Data points are outliers where $q_1 - 1.5(q_3 - q_1) > \text{outlier} > q_3 + 1.5(q_3 - q_1)$, where q_3 = 75th percentile and q_1 = 25th percentile. The width of the box indicates the relative number of samples for each season. If the notches, either side of the median, of two boxes do not overlap, they are significantly different at the 5% probability level (McGill et al., 1978). Note that the y axis is displayed from 60 dB re 1 μ Pa.

Table 2

Mean third-octave levels for the comparative period 14th June–14th November in 2012 and 2013 where the AMAR was recording in both years.

	Mean TOL 14th June–14th November	
	63 Hz	125 Hz
2012	90.0	94.7
2013	88.1	93.3

Table 3
Long-term mean and percentile third-octave levels (TOLs) given in dB re 1 μ Pa.

Period	63 Hz TOL				125 Hz TOL			
	Mean	Percentiles			Mean	Percentiles		
		5th	50th	95th		5th	50th	95th
1st–7th deployments <i>All data presented</i>	91.2	67.6	77.2	93.9	95.0	80.0	87.8	99.5
2nd–6th deployments <i>12 months from Aug 2012 to Aug 2013*</i>	92.6	68.5	78.3	95.3	96.0	81.3	89.5	100.5
2nd–7th deployments <i>All deployments*</i>	91.8	68.1	77.4	94.1	95.3	80.5	88.5	99.9

* Identical deployment configurations of a flotation collar and cloth shroud.

are predominantly winter. Mean maximum difference between sub-sample means created from data sets of increasing size (duration), and the overall mean for the associated deployments decreased from 14.8 dB for 24 h to ~1 dB for the 63-Hz band (Fig. 5; Supplemental Table 5). For the 125-Hz band, the mean maximum difference decreased from 9.5 dB for 24 h to ~1 dB for a shorter duration of 480 h (Fig. 5; Supplemental Table 5).

4. Discussion

We carried out this research to investigate the practicalities of monitoring the suggested indicator bands for the low-frequency noise attribute of the MSFD Descriptor 11 in a bay in the UK. We provide levels from which a trend can be monitored in future at this site.

The third-octave levels were found to be highly variable. The 24-h centred means of the 63-Hz band within Falmouth Bay exhibit greater variation (approx. 38 dB) than the 20 dB measured at four deep ocean sites (van der Schaar et al., 2014). Sound levels in shallow waters are known to be more variable than at deep ocean sites. This is due to the sea surface, water column and seabed properties varying considerably, temporally and spatially, all of which are important in determining acoustic propagation characteristics in shallow coastal environments (Dekeling et al., 2013; Jensen et al., 2011; Merchant et al., 2012b; Urlick, 1983). Consequently, this may also have implications for sampling as the duration required to determine a statistically significant trend, outside the general variability, may be longer in comparison to deep ocean sites. Different management schemes, including differing GES thresholds, may therefore be required for deep and shallow marine sites, especially as the trends in anthropogenic noise may vary with the types of vessels commonly using each area (Dekeling et al., 2013), as well as other sources such as construction and renewable energy sites.

There was greater variation in the 63-Hz third-octave band than in the 125-Hz band. This was also found elsewhere at a coastal site 60 m deep in the USA, where the median 63-Hz and 125-Hz levels were similar, but the 95th percentile level was louder in the 63-Hz band (Bassett et al., 2012). This increased variation may be due to the influence of local shipping as commercial ships typically produce louder sound levels within the 63-Hz band as compared to the 125-Hz band (Arveson and Vendittis, 2000). With increased variability in the 63-Hz band mean levels as compared to the 125-Hz band, longer monitoring to determine statistically significant trends may be required. Similarly, a greater number of samples throughout the year may be required for the 63-Hz band to ensure a representative sample as supported by the sampling effort analysis.

The third-octave levels were found to peak in the winter months and be quietest in the summer with a difference of 6.5 and 7.9 dB between the summer seasons and winter 2012/13 for the 63-Hz band and 3.4 and 3.6 dB for the 125-Hz band, respectively. This indicates a likely seasonal cycle, similar to that seen in other studies such as at Wake Island, West Pacific, and Cape Leeuwin, East Indian Ocean, which exhibit minima in summer and maxima in winter (van der Schaar et al., 2014). However, these cycles are attributed to breaking ice and baleen whale sounds (van der Schaar et al., 2014), which are not likely to apply in Falmouth Bay. In general, there are better propagation conditions during winter months as the sound speed is typically the same throughout the water column due to mixing, whereas in summer, there may be a warm surface duct leading to increased downward refraction of sound waves and, therefore, increased bottom loss (Jensen et al., 2011). This improved propagation in winter may be contributing to the observed louder average sound levels during this season. Additionally, wave height was found to significantly affect third-octave levels, likely contributing to increased third-octave levels with increased wave height in winter. Monitoring is therefore required throughout the year,

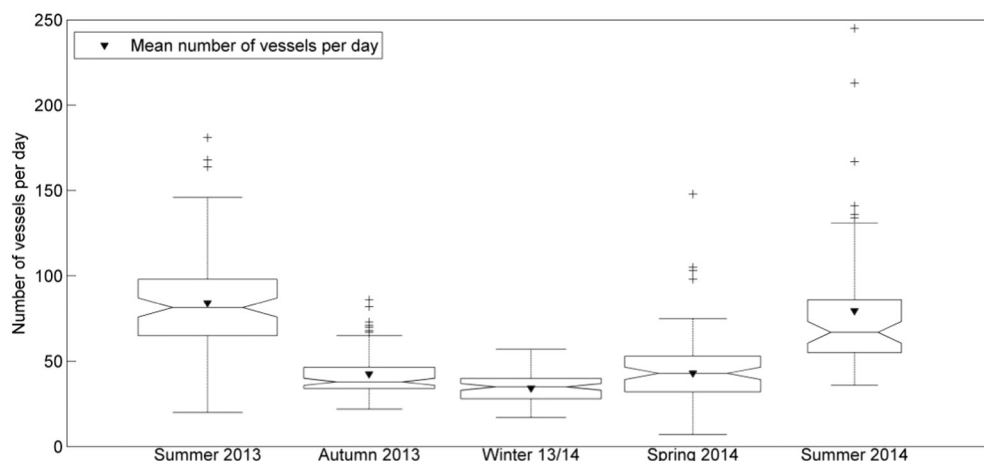


Fig. 4. Seasonal vessel numbers in Falmouth Bay per day from AIS data. The median is given by the centre of the box. The width of the box indicates the relative number of days contributing to each season.

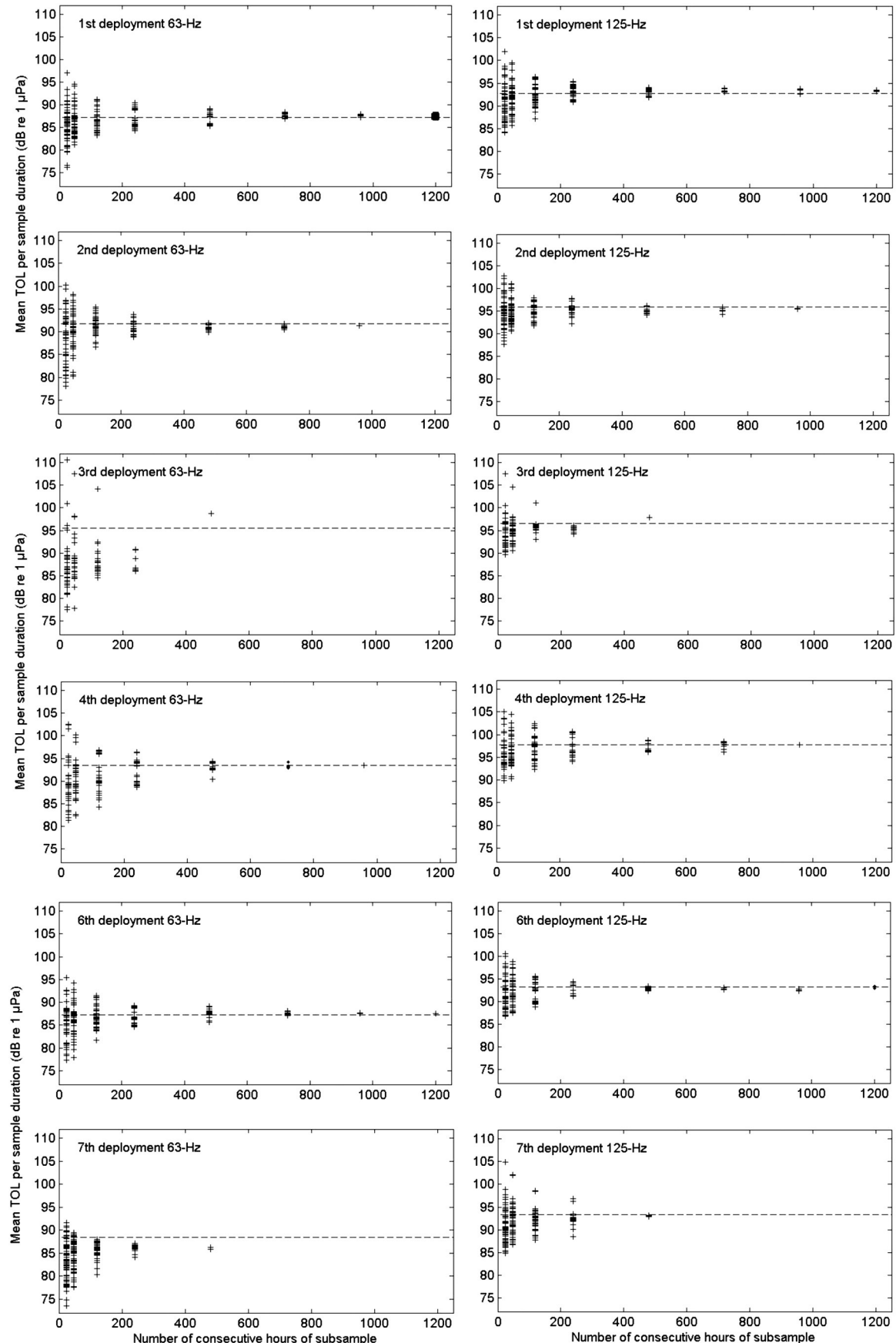


Fig. 5. Mean third-octave levels for each subsample. The dashed line represents the overall mean for the deployment.

sampling each season, to provide a representative yearly mean for the MSFD. These seasonal levels could also be reported, allowing monitoring of such variations.

The average sound levels were found to be louder within the 125-Hz band than in the 63-Hz band. This is in contrast to other results reported in the literature, where measured third-octave levels are more than 10 dB quieter in the 125-Hz band than in the 63-Hz band (Andrew et al., 2002; Chapman and Price, 2011; Hildebrand, 2009). These are recorded in locations much deeper than Falmouth Bay. It is possible that, due to the small depth ranges in our study area, the contribution of distant low-frequency shipping noise is reduced compared to deeper areas. Merchant et al. (2012b) attributed higher sound levels in the intermediate frequencies in Falmouth Bay to favourable propagation characteristics and to high numbers of small recreational boats, which tend to produce sounds at higher frequencies (Picciulin et al., 2008; Rako et al., 2013; Richardson et al., 1995). The 63-Hz band in coastal sites, such as Falmouth Bay, may therefore not be as representative of the wider trends in shipping noise, as similarly suggested in Merchant et al. (2014). This also supports differing management initiatives for deep and coastal locations, particularly as coastal areas are important with regard to human–ecosystem interaction. Merchant et al. (2014) found a correlation between the 250-Hz and the 500-Hz third-octave bands and noise exposure in a wider frequency band of 50 Hz to 1 kHz approximately corresponding to shipping noise in two coastal sites 19 m and 45 m deep. This suggests that higher frequency bands may also be appropriate for monitoring shipping noise in shallow coastal sites.

The sound levels for the 2nd to 6th deployments (August 2012 to August 2013) corresponded to identical deployment configurations, using a flotation collar and a cloth hat to reduce flow noise. For this period, the yearly mean sound levels were 92.6 and 96.0 dB re 1 μ Pa for the 63-Hz and 125-Hz bands, respectively. The long-term means reported in this study are similar to the yearly means for the 63-Hz band over 3 years at four different deep ocean sites around the world, which ranged from 90.0 dB to 96.3 dB (van der Schaaf et al., 2014). There is currently no target level or trend for the MSFD as there is a lack of evidence regarding the sound levels that constitute GES (Dekeling et al., 2013; Van der Graaf et al., 2012). The sound levels presented here represent levels from which a trend can be monitored in the future.

Although wave height is not strongly correlated with sound levels, as waves that may not be breaking contribute to wave height (Felizardo and Melville, 1995), wave height was used to provide an indication of the wind-driven contribution to sound levels as they were available from a nearby Wave Buoy (~150 m) providing accurate data. Both third-octave bands were found to exhibit a significant relationship with wave height indicating that both bands are affected by natural contributions.

Flow noise is considered self-noise and should be excluded in the analysis of levels and trends for MSFD monitoring (Robinson et al., 2014; Van der Graaf et al., 2012). Flow noise is understood to predominantly affect frequencies < 100 Hz (Robinson et al., 2014). However, it has been detected at frequencies up to 160 Hz in Scotland (Merchant et al., 2014) and up to 800 Hz in Chile where the maximum frequency exhibiting identifiable flow noise increased with current speed (Bassett et al., 2014). For Falmouth Bay, flow noise was found to potentially affect the 63-Hz third-octave level as the effect was found to be significant. However, the interaction between the shroud and tide speed was also found to be significant suggesting that the use of the shroud reduced the flow noise. A reduction in the difference between sound levels at peak flow times and at other times was found of 3.5 dB between the 2nd and the 3rd deployments when the shroud was absent and present, respectively. Hydrophone cage shrouds have also been used on other systems to reduce flow noise (Sousa-Lima et al., 2013). Tide speed was found not to exhibit a significant effect on the 125-Hz band noise level. This is consistent with other results in the literature where higher frequencies are less affected by flow noise.

The results here indicate that for representative monitoring of the 63-Hz band for the MSFD, measures to reduce flow noise should be considered.

The 63-Hz and the 125-Hz bands are used by the MSFD as indicators for shipping noise, as they are thought to contain maximal anthropogenic contributions with minimal natural contributions (Tasker et al., 2010). However, the results in the present study suggest that natural sources and propagation characteristics may also influence the sound levels in these bands. This suggests that when comparisons are made between and among sites, or between and among seasons, this should be done with knowledge of the local environmental contributions, including depth, bathymetry, weather conditions, and presence of biological sources that produce sounds at low frequencies. This would be particularly important if monitoring absolute levels for the MSFD.

Both distant shipping and intermittent local vessel traffic have previously been found to affect the sound levels in Falmouth Bay, mostly in the frequency range 0.01–1 kHz (Merchant et al., 2012b). However, the peak frequency identified within the intermittent ship noise in Falmouth Bay was 315 Hz (Merchant et al., 2012b), above the MSFD indicator bands. Therefore, it would be expected that the 63-Hz and the 125-Hz bands include contributions from shipping but that the loudest sounds may be excluded.

The number of unique vessels in Falmouth Bay per day and the third-octave levels display contrasting seasonal trends, with the highest number of vessels occurring in the summer seasons (2013 and 2014) and the fewest unique vessels occurring in winter 2013/2014. This likely suggests that the third-octave bands of 63 Hz and 125 Hz are not wholly representative of the AIS-carrying vessel traffic at this site. However, in combination with wave height and tide speed, the numbers of AIS-transmitting vessels were found to be significant contributors to both bands during the summer and autumn in 2013. It is already known that shipping sound levels and peak frequencies can depend on ship speed and size (Arveson and Vendittis, 2000; McKenna et al., 2013; Richardson et al., 1995). Therefore, other shipping parameters may additionally influence the local sound levels, such as vessel size, speed, or condition; and the number of vessels anchored within the bay, as on-board generators are likely to remain running even if main propulsion engines are not operational. Overall, third-octave bands are likely not solely indicative of ship numbers and additional parameters need to be taken into account. As such, further research to investigate the relationship of vessel traffic on third-octave bands with the changing seasons would be beneficial.

As well as commercial vessel traffic, there is also considerable recreational boating in Falmouth Bay (Latham et al., 2012). It would be expected that it hosts more recreational boats in the summer season. Although small recreational boats are not required to carry AIS, many do so voluntarily and there are greater numbers of AIS-carrying vessels in Falmouth Bay in summer. However, the mean 63-Hz and 125-Hz third-octave levels are at their minima in summer. Small boats were found to exhibit their maximum sound pressure levels in the frequency range 160–250 Hz (Picciulin et al., 2008), which suggests that the peak sound levels, and the associated putative seasonal summer increase, may be undetected by the MSFD indicator bands. Small personal watercraft (PWC; such as jet skis) were recorded in Australia and found to produce sounds above ambient sound levels in the range 100 Hz to 10 kHz with an additional peak at 15 Hz (Erbe, 2013), which may also contribute to the sound levels in Falmouth Bay, particular in the summer, although they are fewer than other recreational vessels. In a study of a coastal area with high anthropogenic impact in Croatia, the third-octave levels were found to be considerably louder (up to ~4 dB) in the frequency range 350 Hz to 2 kHz during the tourist season (summer) compared to the non-tourist season, with a reduced difference ranging from negligible to 1.5 dB in the frequency range 60 to 250 Hz (Rako et al., 2013). This effect is unlikely to be significant in deeper ocean sites further from the coast, but the effect of small, recreational vessels on coastal underwater sound levels may be biologically

significant and not suitably incorporated into the current proposed form of the MSFD (Graham and Cooke, 2008; Haviland-Howell et al., 2007; Rako et al., 2013; Sebastianutto et al., 2011). Monitoring higher frequency bands may therefore be useful, particularly in coastal areas where there is recreational boating activity.

The subsample mean third-octave levels were found to decrease in their departure from the overall mean for their respective deployments with increasing duration. A subsample of 24 h was found to vary up to 18 dB from the true overall mean for the respective deployment. Short durations of sampling, of less than 10 days, per season may therefore give unrepresentative mean third-octave levels. However, for subsamples of 30 days, the maximum departure from the mean decreased to <2 dB and to <1 dB by 40 days. The standard for calibration is often within 1 dB of the expected sound level (McDonald et al., 2006; Robinson et al., 2014; Wursig and Greene, 2002). As such, a value within 2 dB of the mean is considered reasonable. Therefore, at least for locations similar to Falmouth Bay, sampling durations of at least 30 days per season are recommended for future MSFD monitoring.

The low-frequency sounds measured within these MSFD bands have varying relevance to different groups of marine species. They are above the frequency range of functional hearing for odontocetes, and within the range of baleen whales (Southall et al., 2007). The higher band (125 Hz) is within the pinniped range (Southall et al., 2007) and within the best hearing sensitivity range of fish, at 100 Hz–2 kHz (Kastelein et al., 2008) (although hearing abilities vary greatly among fish species (Hastings and Popper, 2005)). The effects of long-term exposure to shipping noise are little understood (Tyack, 2008). Chronic effects will be harder to determine than those of immediate responses, for which some criteria have been suggested (Popper et al., 2006; Southall et al., 2007). However, there is evidence for a wide range of biologically significant impacts from chronic low-frequency anthropogenic noise. For example, animals have been found to compensate for increased noise by changing the volume of their signals (Holt et al., 2009), their frequency (Parks et al., 2007), or the vocalisation rate (Picciulin et al., 2012). Avoidance of an area by cetaceans is also thought to have occurred due to noise (Bejder et al., 2006; Bryant et al., 1984). These responses may have costs to fitness, which are still largely unknown (Tyack, 2008). There is evidence to suggest that ship noise causes stress in marine species including right whales (Rolland et al., 2012) and shore crabs (Wale et al., 2013b). Long-term stress can negatively affect growth, reproduction, and the immune system (Romero and Butler, 2007). Low-frequency anthropogenic noise also has the potential to affect vital life history processes in invertebrates including metamorphosis, settlement time, feeding, and predator avoidance (Pine et al., 2012; Wale et al., 2013a; Wilkens et al., 2012). Ship noise is therefore audible to a wide range of marine species and has the potential to cause significant negative effects to individuals. Further, there is little understanding regarding the effect of chronic noise exposure at the population level and for host ecosystems, particularly over extended time periods (Bejder et al., 2006). An additional challenge is the potential for cumulative effects of noise in association with other human-induced stressors e.g., pollution and ocean acidification (Boyd et al., 2011).

Given the paucity of information regarding impacts, determining Good Environmental Status with respect to ambient sound is highly complex. Sound levels at night time, with low vessel noise, for example, have been used as an indicator of natural conditions (Gervaise et al., 2012); a similar approach might be used to set site-specific seasonal GES targets, although further research is required to validate such an approach.

5. Conclusion

There is considerable variation within the third-octave bands throughout the year, with the greatest degree of variability in the 63-Hz band. Therefore, when monitoring sound levels for the MSFD, samples should be taken throughout the year, and over sufficient durations,

to ensure a representative yearly mean. To detect a statistically significant trend in the sound levels, monitoring will need to be for a suitable length of time, the duration of which will largely be driven by variability. Due to its higher level of variability, the sampling programme may need to be based on the 63-Hz band.

In Falmouth Bay, the third-octave levels are louder in the 125-Hz band than the 63-Hz band, in contrast to deeper ocean sites. This may be due to an increased contribution from local, coastal vessel traffic, and less favourable propagation conditions for low frequencies, affecting the contribution from distant shipping. Therefore, shallow and deep ocean sites may require different management initiatives. The monitoring of third-octave bands with higher centre frequencies may be useful in shallow coastal environments affected by recreational boating.

The natural environmental conditions of wave height and tidal flow have been found to affect the sound levels at this site. Therefore, site-specific targets may be required, accounting for natural contributions to local sound levels. Practical measures may be required to reduce flow noise during the measurements, and care should be taken when comparing between sites.

This research provides information on the current third-octave levels near a busy UK port. We highlight the need to monitor over a long term, due to the high variability. The presented analysis has implications for the management initiatives that might be implemented under the EU MSFD Descriptor 11. Our work also underlines the need for continued focused research, both on methods to collect data and on the biological implications of anthropogenic acoustic energy on sessile and mobile species and their habitats, influencing the longer-term ability to deliver GES.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.marpolbul.2016.06.021>.

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